

Upgraded experiments with super neutrino beams

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We compare the sensitivities of possible upgrades of superbeam experiments, namely NO ν A, T2KK and experiments with wide band beams, to a nonzero θ_{13} , to CP violation and to the neutrino mass hierarchy. For the proposed luminosities, we find the best nominal CP violation performance for T2KK and the best mass hierarchy performance for a wide band beam experiment. However, for equal luminosities, the physics concept on which NO ν A is based has the best potential for discovering CP violation.

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Introduction. Extensive recent experimental exploration has revealed that neutrinos are massive [1]. This finding necessitates the existence of physics beyond the Standard Model of particle physics. Massive neutrinos may also have far-reaching consequences for cosmology. They may shed light on the origin of the baryon asymmetry in our universe and on why the universe is in an accelerating phase in its expansion. It is therefore imperative that the origin of neutrino masses be determined.

A plethora of neutrino mass models have been proposed and precise knowledge of neutrino parameters is required to test them. Specifically, the value of the mixing angle θ_{13} and the type of mass hierarchy (*i.e.*, whether $m_1, m_2 < m_3$, called the normal hierarchy or $m_1, m_2 > m_3$, called the inverted hierarchy) will help distinguish between models based on lepton flavor symmetries, models with sequential right-handed neutrino dominance and more ambitious models based on GUT symmetries [2]. A recent survey of 61 models that are consistent with current oscillation data and have concrete predictions for θ_{13} found that half of them predict $\sin^2 2\theta_{13} > 0.015$ [3]. GUT models and models with right-handed neutrino dominance naturally yield a normal hierarchy and a relatively large θ_{13} (although in a few GUT models, an inverted hierarchy can be obtained with fine-tuning). Models based on leptonic symmetries can easily accommodate an inverted hierarchy and small θ_{13} . Thus, experimental establishment of an inverted hierarchy and small θ_{13} would lend support to models based on leptonic symmetries and reduce the interest in GUT models and models with right-handed neutrino dominance. On the other hand, if θ_{13} is found to be large, distinguishing between the three different classes of models will be difficult. However, if in addition to a large θ_{13} , the hierarchy is found to be inverted, it will be possible to exclude the subclass of SO(10) GUT models that employ so-called lopsided mass matrices because they predict a normal hierarchy.

Clearly, experiments with good sensitivity to θ_{13} and

the mass hierarchy are indispensable for sifting out a restricted class of neutrino mass models. Precision measurements of deviations of the atmospheric oscillation angle θ_{23} from $\pi/4$ are also useful in distinguishing between models. The deviation from maximal atmospheric mixing provides an excellent probe of how symmetry breaking occurs in models based on leptonic symmetries. The Dirac CP phase δ_{CP} in the neutrino mixing matrix may be related to the CP violation required for leptogenesis (which is a direct consequence of the seesaw mechanism) and it may therefore be possible to test both the seesaw and the origin of the baryon asymmetry in our universe by measuring this CP phase.

If neutrinos do not have approximately degenerate masses, the sensitivity of experiments seeking to detect neutrinoless double beta decay (thereby confirming that neutrinos are Majorana particles), is strongly impacted by whether the mass hierarchy is normal or inverted.

Long-baseline neutrino experiments offer the only way to establish a nonzero θ_{13} , to determine the mass hierarchy and to detect neutrino CP violation. There are two strategies being considered for a future experimental program, with combinations of different types of neutrino beams and detector technologies. Off-axis beams have a narrow beam energy, permitting a counting experiment at an oscillation maximum with low background. Wide band beams have a higher flux and allow an experiment that utilizes spectral energy information, but requires large sophisticated detectors with very good energy resolution and neutral-current rejection to reduce backgrounds.

The Tokai-to-Kamioka (T2K) experiment [4] will use an off-axis beam. The proposed NuMI Off-axis ν_e Appearance (NO ν A) experiment [5] (and its second phase) and the Tokai-to-Kamioka-and-Korea (T2KK) extension [6] of the T2K experiment also plan to employ off-axis beams. Recently, workers at Brookhaven National Laboratory (BNL) [7] have advocated a wide band beam (WBB) experiment, the virtues of which have been in-

vestigated in Ref. [8]. With the looming possibility of a Deep Underground Science and Engineering Laboratory (DUSEL) [9] in the U.S., and its capacity to house very large detectors, it is timely to evaluate the relative merits of the two experimental approaches with upgraded superbeams.

So far, the experimental options and assumptions made in analyses have been so diverse that an objective comparison is not possible. For example, one experiment may seem to have greater sensitivity simply because the exposure assumed is much larger than that of another experiment.

We carry out a technically comprehensive study with a realistic treatment of systematic errors, correlations and degeneracies [10]. Our goal is to clarify the physics reach of the different proposals by analyzing them on an equal footing. We present the sensitivities of the experiments to a nonzero θ_{13} , the mass hierarchy and to CP violation *as a function of exposure* so that merits of the different experimental techniques are evident.

Experimental setups and analysis techniques.

We use the GLoBES software [11] for our simulations. Table I displays parameters of the experiments.

Our NO ν A simulation is based upon the proposal [5] and recent studies on the performance of a Liquid Argon time projection chamber (LArTPC) [12]. We assume NO ν A phase II (3 years ν and 3 years $\bar{\nu}$) with a 100 kt LArTPC, which has a 0.8 signal efficiency and only beam intrinsic ν_e and $\bar{\nu}_e$ backgrounds. We split the event sample into quasi-elastic (QE) events with 5% energy resolution and the non-QE charged current events with 20% energy resolution. We have carried out a dedicated optimization study in baseline versus off-axis angle plane whose details can be found in [13]. We find that the best location for all measurements is the Ash River site (12 km off-axis at $L = 810$ km) where NO ν A phase I is located. None of the alternative sites such as in Ref. [14] performs as well as Ash River. This result holds even if NO ν A phase I data is taken into account.

For the WBB experiments, we use the simulation from Ref. [8] and choose the Fermilab-Homestake baseline $L = 1290$ km for reference. We consider two possible detector technologies: A 300 kt water Cherenkov detector and a 100 kt liquid argon TPC. We assume that five years of neutrino running with a 1 MW beam will be followed by five years of running with a 2 MW beam.

For the NO ν A and WBB setups, we use a systematic uncertainty of 5% on both signal and background, uncorrelated between neutrino and antineutrino channels.

For our T2KK simulation, we employ the values from Ref. [6] with a 2.5° off-axis beam. Our simulation is based upon the analysis of the Tokai-to-HyperKamiokande experiment in Ref. [15], *i.e.*, we use the spectral information for quasi-elastic (QE) events, and the total event rate for all charged current (CC) events. We include 5% signal and background errors, as well as a 5% background en-

ergy calibration error which are correlated between the two detectors in Japan and Korea, but uncorrelated between the neutrino and antineutrino channels.

We adopt $\Delta m_{21}^2 = +8 \cdot 10^{-5} \text{ eV}^2$, $\Delta m_{31}^2 = +2.5 \cdot 10^{-3} \text{ eV}^2$, $\sin^2 \theta_{12} = 0.3$, $\sin^2 \theta_{23} = 0.5$ for the oscillation parameters. We assume that the atmospheric oscillation parameters are measured to 10%, the solar parameters are measured to 4%, and the matter density along the baseline is known to 5%. We include all correlations and degeneracies in the analysis. Details of our simulations are presented in Ref. [13].

Results. In Fig. 1 we show the comparison of super-beam upgrades in the configurations of Table I for the $\sin^2 2\theta_{13}$, CP violation, and normal hierarchy discovery reaches. This comparison illustrates which of the planned experiments has the best physics potential. Interestingly, the optimal physics performance depends on the performance indicator. The $\sin^2 2\theta_{13} \neq 0$ discovery reaches are very similar for all the experiments. T2KK has the best CP violation potential. The WBB experiments can detect the mass hierarchy down to $\sin^2 2\theta_{13} \simeq 10^{-2}$ for all values of δ_{CP} , which makes them the best upgrade for the mass hierarchy (as a result of their long baseline and high energy and consequently strong matter effects). However, this figure does not permit a balanced assessment of which experiment is the best physics concept because of the very different assumptions for the luminosities in each proposed experiment.

In order to make an unbiased comparison of the physics potentials of the experimental setups we consider their sensitivities as functions of *exposure* which we define to be $\mathcal{L} = \text{detector mass [Mt]} \times \text{target power [MW]} \times \text{running time [} 10^7 \text{ s]}$. The target power represents the bottleneck in technological difficulty. Note that instead of the running time in years, the exposure uses the actual available time of the accelerator for the neutrino experiment. For NO ν A and the WBB, we use $1.7 \cdot 10^7$ seconds uptime per year, and for T2KK, we use 10^7 seconds uptime per year (as anticipated in the corresponding documents). Note that this definition does not account for the level of sophistication of different detector technologies, but it will allow for an identification of the break-even point of the detector cost. We show the exposure for the discussed experiments in the last column of Table I. It is evident that NO ν A has the lowest exposure, whereas T2KK has the highest. While we will show a normalized comparison of the experiments based on the exposure, it is noteworthy that there may be other issues, such as robustness of systematics and a different experiment optimization that may modify the conclusions. We will discuss these issues elsewhere [13].

In Fig. 2 we show the discovery reaches for $\sin^2 2\theta_{13}$, CP violation, and normal mass hierarchy versus the exposure for a fraction of δ_{CP} of 0.5 (see figure caption). The NO ν A curves for the $\sin^2 2\theta_{13}$ and CP violation discoveries are consistently (for any exposure) lower than

Setup	POT ν /yr	t_ν [yr]	POT $\bar{\nu}$ /yr	$t_{\bar{\nu}}$ [yr]	P_{Target} [MW]	L [km]	Detector technology	m_{Det} [kt]	\mathcal{L} [Mt MW 10^7 s]
NO ν A	$10 \cdot 10^{20}$	3	$10 \cdot 10^{20}$	3	1 (ν)	810	Liquid argon TPC	100	1.02
WBB+WC	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν) + 2 ($\bar{\nu}$)	1290	Water Cherenkov	300	7.65
WBB+LAr	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν) + 2 ($\bar{\nu}$)	1290	Liquid argon TPC	100	2.55
T2KK	$52 \cdot 10^{20}$	4	$52 \cdot 10^{20}$	4	4 (ν)	295+1050	Water Cherenkov	270+270	17.28

TABLE I: Setups considered, numbers of protons on target per year (POT/yr) for the neutrino and antineutrino running modes, running times in which these be achieved, corresponding target power P_{Target} , baselines L , detector technology, detector mass m_{Det} , and exposure \mathcal{L} .

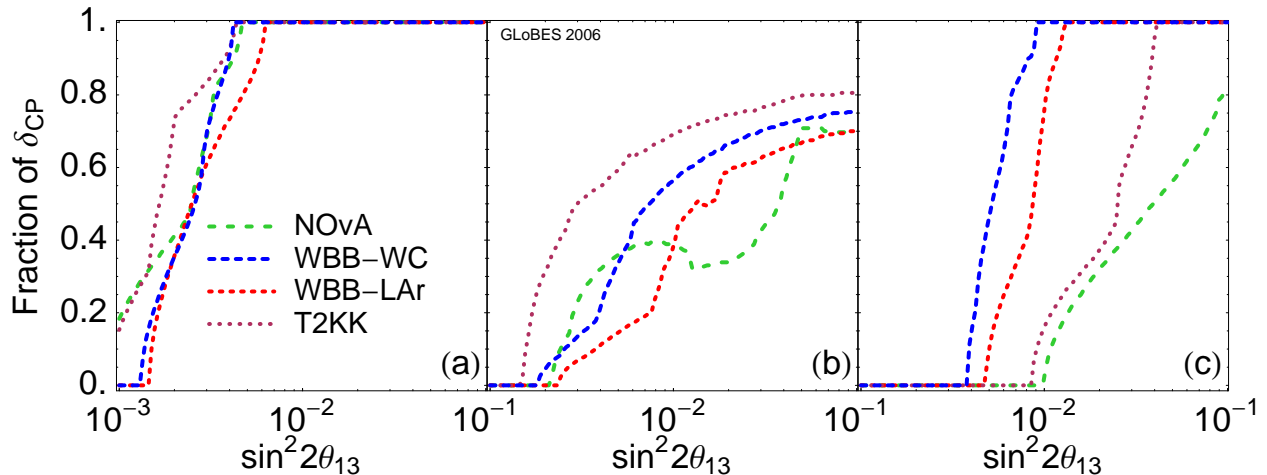


FIG. 1: Comparison of superbeam upgrades in the configurations of Table I at the 3σ C.L. The plots show the discovery reaches for a nonzero $\sin^2 2\theta_{13}$, CP violation, and the normal hierarchy. The “fraction of δ_{CP} ”, quantifies the fraction of all (true) values of δ_{CP} for which the corresponding quantity can be measured.

the ones of the other experiments, whereas the curves for the WBB experiments are lower than any other curve for the mass hierarchy discovery. If all experiments were operated at the same exposure, these experiments would yield the best results. All of the curves scale relatively smoothly as a function of exposure except the CP violation curve for NO ν A. A further luminosity increase could enhance the NO ν A potential for CP violation considerably (by enabling the resolution of degeneracies at this confidence level). The other setups are relatively insensitive to small variations in exposure. For CP violation, the WBB and T2KK concepts are more or less equivalent since the curves almost overlap. The WBB-WC and the T2KK curves intersect at some points. These intersections limit the exposure ranges in which one experiment dominates the other. For example, for $\sin^2 2\theta_{13}$, T2KK plans to operate with an exposure for which the WBB-WC concept would perform slightly better, whereas a significantly lower exposure would make T2KK the more sensitive experiment. Finally, one can read off the break-even point between the water Cherenkov and liquid argon-technologies in WBB experiments. For example, for $\sin^2 2\theta_{13}$, the water Cherenkov and liquid argon technologies are separated by about a factor of 2.5

in exposure, which means that liquid argon is the choice of technology if the cost per kt of liquid argon is smaller than the cost for 2.5 kt water. Note that the corresponding sensitivities to CP violation and the mass hierarchy are quite similar.

Summary and conclusions. It is crucial that the mixing angle θ_{13} , the nature of the neutrino mass hierarchy and whether CP is violated in the neutrino sector, be determined to complete the parameter set that defines the neutrino mass matrix. This program is of fundamental value for understanding the origin of neutrino masses and for selecting between neutrino mass models.

In the not-too-distant future, the planning stage for long-baseline neutrino experiments with super neutrino beams and large detectors will end. We have provided the first analysis of various experimental configurations on an equal-footing by expressing their sensitivities as functions of exposure. By enabling a balanced comparison, our study identifies which physics concept is optimal for which measurement. If a large liquid argon TPC can become a reality, our analysis indicates that with a modest increase in exposure, an upgraded NO ν A experiment has much better sensitivity to a nonzero θ_{13} and to CP violation than previous estimates suggested. However,

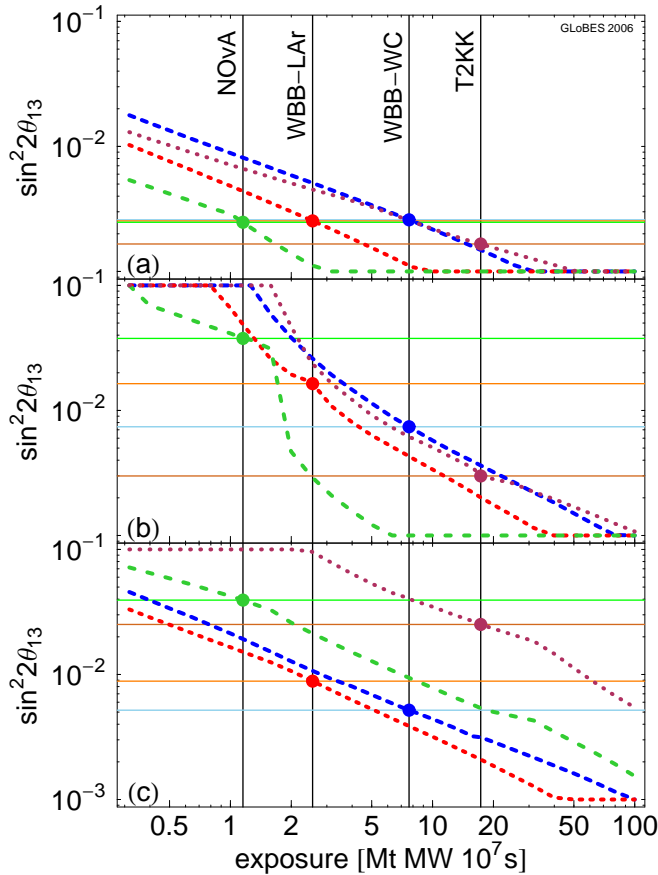


FIG. 2: The discovery reaches (at the 3σ C.L.) for nonzero $\sin^2 2\theta_{13}$, CP violation, and the normal hierarchy as functions of exposure. The line types are the same as in Fig. 1 and the vertical lines mark the proposed luminosities as listed in Table I. The curves correspond to a fraction of δ_{CP} of 0.5, *i.e.*, the median of the distribution. This means that the performance will be better for 50% of all cases of δ_{CP} and worse for 50% of all cases of δ_{CP} ; it is sometimes referred to as the “typical value of δ_{CP} ”.

the longer baselines planned for experiments with wide band beams offer better sensitivity to the mass hierarchy.

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